Change in Surface Soil Carbon under Rotated Corn in Eastern South Dakota

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A diversified crop rotation may reduce fertilizer N inputs for corn (*Zea mays* L.) and increase soil organic C (SOC). Our objectives were to determine the effects of crop rotation and fertilizer N on soil C within the surface soil (0–15-cm depth). Rotations were started in 1990 on a Barnes sandy clay loam near Brookings, SD. Measurements of SOC began in 1996. Primary tillage since 1996 was chisel plow. All crop residues were returned to the soil. Rotations were continuous corn (CC), corn–soybean [*Glycine max* (L.) Merr.], and corn–soybean–wheat (*Triticum aestivum* L.) companion seeded with alfalfa (*Medicago sativa* L.)–alfalfa hay (CSWA). Uncropped treatments included perennial grasses. Corn N treatments were based on the soil NO_3 test and yield goal. Corn was fertilized for a grain yield of 8.5 Mg ha^{-1} (high N), 5.3 Mg ha^{-1} (mid N), and no N. Under grass, SOC increased 3.8 Mg C ha^{-1} from 1996 to 2006. Continuous corn under high N returned 34% more aboveground plant C (PC) to the soil compared with the CSWA rotation, but this did not offset the SOC loss. Under high N, there was a loss of 2.3 Mg C ha^{-1} in the surface soil from CC and a gain of 0.3 Mg C ha^{-1} from CSWA (1996–2006). There was a significant effect of fertilizer N addition and rotation on SOC. A combination of greater crop diversity and fewer tillage operations on CSWA, compared with CC, probably contributed to a balance of SOC (return of PC ≈ loss of SOC).

Abbreviations: SOC, soil organic carbon; CC, continuous corn; CS, corn–soybean rotation; CSWA, corn–soybean–wheat companion seeded with alfalfa–alfalfa hay rotation; PC, aboveground plant carbon.

With increased interest in global climate change, there is a new awareness of the potential for using innovative soil and crop management to sequester atmospheric C. Crop rotation, residue, fertility, and tillage management are key tools that have a direct impact on soil C storage and the sustainability of the soil resource. It is difficult to generalize the effects of crop rotation on production and associated SOC gains or losses. Johnson et al. (2006) has estimated the minimum source C inputs (aboveground plant C) required for maintaining SOC to be 2.5 ± 1.0 Mg C ha^{-1} yr^{-1} under moldboard-plow systems from 13 field experiments.

Generally, the increased diversity of crops grown in rotation enhances the sustainability of agriculture systems because crops grown in rotation, with similar off-farm inputs, often have greater yield than when grown in monoculture (Mannering and Griffith, 1981; Dick et al., 1986; Higgs et al., 1990; Pikul et al., 2005). Crop rotations that include legumes also increase soil N levels (Peterson and Varvel, 1989; Raimbault and Vyn, 1991). Russell et al. (2005) found, on a study in Iowa, that cropping systems containing alfalfa had the highest SOC stocks in the top 100 cm, but also found no correlation of yield and SOC stocks under any cropping system.

A clear statement on the cause and effect of crop rotation on SOC cannot always be made. On field trials near Mead, NE, Varvel (2006) found that decreases in SOC in the top 30 cm of the soil were about 10% greater under monoculture and 2-yr cropping systems than a 4-yr rotation. In that study, however, even the diversified 4-yr crop rotation lost SOC or balanced near no change during a 10-yr period (Varvel, 2006). Russell et al. (2005) found, on experimental sites in Iowa, that the rate of gain of SOC in the top 15 cm under fertilized CC, compared with a fertilized rotation of corn–corn–oat (*Avena sativa* L.)–alfalfa (CCOA), did not differ significantly from zero. At

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another site, Russell et al. (2005) found that both the fertilized CC and CCOA cropping systems gained SOC in the top 15 cm during 12 yr. In a 24-yr study near West Lafayette, IN, SOC sequestration was not affected by rotation (continuous corn or corn–soybean) at any depth interval (Omonode et al., 2006). In the first 15 yr of a crop rotation and fertilizer experiment in southwestern Saskatchewan, however, significant treatment effects on soil organic matter were detected in the top 15 cm (Campbell and Zentner, 1993).

Huggins et al. (1998) assessed land management effects on SOC for several long-term studies in the tallgrass prairie region of the U.S. Corn Belt. The oldest of these studies were the Morrow Plots started in 1876 at the University of Illinois, Champaign-Urbana. On the Morrow Plots, regardless of a change in management in 1967 to return all crop residues to the plots, all rotations showed a gradual decline in SOC of the surface soil with time in both the fertilized and unfertilized series. Rotations investigated by Huggins et al. (1998) were CC, corn–oat, and corn–oat–hay.

West and Post (2002) reviewed 67 long-term agricultural experiments from around the world and concluded that SOC sequestration increased with decreasing soil disturbance or enhanced rotation diversity. Generally, changing from monoculture to rotational cropping or increasing the number of crops in rotation did not result in sequestering as much SOC as did a change to no tillage. Furthermore, changing from CC to a corn–soybean rotation (CS) did not result in increased C storage. Importantly, West and Post (2002) pointed out that in practice there is often a simultaneous change in tillage that accompanies a change in crop rotation. When tillage is decreased and rotation complexity is enhanced simultaneously, then the short-term (15–20-yr) increase in SOC will primarily be caused by the change in tillage and the subsequent decrease in the rate of SOC decomposition. Long-term (40–60-yr) increases in SOC will be primarily caused by the rotation enhancement and subsequent change in residue input and composition (West and Post, 2002).

Thus, it is not surprising that regional findings on the effects of increased crop diversity on SOC sequestration often fall short or are contradictory to expectations that SOC levels improve on conversion to a diversified rotation. Few field trials are conducted according to a unified set of materials and methods and the number of tillage operations used in diversified rotations often differs from those used as an experimental control. An important question was posed by Kemper (1997): soil organic matter levels have decreased in agricultural soils during the past 100 yr—how long will it take to rebuild soil organic matter on a degraded soil? Partial answers to this question are collectively contained within rotation experiments of the past and those that are ongoing. Our work centered on the hypothesis that if crop rotation diversity is increased then there will be a corresponding increase in surface soil C. Our objectives were to determine the effects of crop rotation and fertilizer N on soil C sequestration within the surface soil.

MATERIALS AND METHODS

Experimental Site

The study was located on the Eastern South Dakota Soil and Water Research Farm near Brookings, SD (44°19′ N, 96°46′ W, and 500-m elevation), on a Barnes soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) with nearly level topography. Annual precipitation is 580 mm. Before initiating the rotation experiment in 1990, the study site was cropped (1972–1978) to oat and barley (*Hordeum vulgare* L.), corn rotated with soybean (1979–1987), soybean (1988), and spring wheat (1989). Soil measurements taken from 1996 to 2006 are reported here.

Experimental Design and Management

Whole plots (rotations) in the split-plot experiment were arranged as a randomized complete block with three replications. Split plots were N management. All crop phases of each rotation were present every year. Individual plots were 30 m long by 30 m wide. Crop rotations, since 1990, included continuous corn (CC), a 2-yr rotation of corn–soybean (CS), and a 4-yr rotation of corn–soybean–spring wheat companion seeded with alfalfa–alfalfa (CSWA). In the 4-yr rotation, spring wheat was used as a grain crop (3rd yr) and alfalfa was harvested for hay in the 4th yr of the rotation and then terminated. Pikul et al. (2005) provided details on agronomic management, corn yield, soil sampling, and the efficiency of N and water use by corn in these rotations.

Uncropped plots included three treatments and three replications of perennial grasses. Treatments were warm-season grasses, cool-season grasses, and a mix of warm- and cool-season grasses. Cool-season species were intermediate wheatgrass [*Elytrigia intermedia* (Host) Nevski], orchardgrass (*Dactylis glomerata* L.) and creeping foxtail (*Alopecurus arundinaceus* Poir.). Warm-season species were switchgrass (*Panicum virgatum* L.) and big bluestem (*Andropogon gerardii* Vitman). Grass plots have been burned in the spring every other year.

Primary tillage since 1996 was with a chisel plow in the fall of the year. The depth of chisel-plow tillage has generally been <20 cm. Before 1996, primary tillage was with a moldboard plow in the fall of the year. From 1996 to 2000, corn and soybean were cultivated twice during the early growing season. After 2000, cultivation was done only once per year. Seedbeds were prepared using a tandem disk and field cultivator. Crops common to all rotations were seeded with the same rate and cultivar and on the same date in a given year. Growing-season precipitation and corn planting information are shown in Table 1.

Corn N treatments included corn fertilized for a yield goal (YG) of 8.5 Mg grain ha^{-1} (high N), corn fertilized for 5.3 Mg grain ha^{-1} (mid N), and corn without N fertilizer (no N). The total soil NO_3 (TSN) test was used to estimate the fertilizer N prescription (NP) for corn (Gerwing and Gelderman, 1996). At the start of the experiment the TSN test was the recognized method in eastern South Dakota for selecting a rate of fertilizer N based on corn yield goal. The method has been used throughout the life of these rotations. On each subplot under high N and mid N, the NP was calculated as NP = 0.022YG – TSN. Adjustment to the NP for a previous crop or sampling date was not made (Pikul et al., 2005).

Crop Measurements

Grain yields were measured with a Massey Ferguson MF 8-XP research plot combine (Kincaid Equipment Manufacturing, Haven, KS) equipped with an electronic weigh bucket. On each corn and soybean plot, eight rows, 30 m long, were measured for grain yield. On each wheat plot, two swaths, 1.5 m wide by 30 m long, were measured for grain yield. Corn, soybean, and wheat grain yields were adjusted to 15.5, 13, and 13% moisture contents, respectively. Alfalfa

Table 1. Corn planting date, cultivar (1996–2001 Pioneer, 2002–2003 Golden Harvest H-, 2004–2005 Dekalb), seeding rate, last cultivation, harvest date, growing season precipitation, and growing degree days for 1996 through 2005. Weather data courtesy of South Dakota State Climatologist, Brookings, SD.

Parameter	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
					Corn management					
Planting date	16 May	8 May	30 Apr.	12 May	3 May	14 May	3 May	8 May	5 May	4 May
Cultivar	3769	3769	3751	3751	37H24	37H24	7476RR	7476RR	46–26	46–26
Seeds ha^{-1}	29620	30500	30056	31336	29185	29795	34848	36590	36590	34848
Cultivation	26 June	25 June	16 June	21 June	27 June	21 June	26 June	30 June	25 June	27 June
Harvest date	23 Oct.	10 Oct.	8 Oct.	6 Oct.	10 Oct.	17 Oct.	15 Oct.	15 Oct.	26 Oct.	25 Oct.
					Precipitation†, mm					
Apr.	7	50	46	106	37	150	33	49	41	47
May	125	30	39	87	171	48	78	70	158	96
June	72	65	52	65	76	93	62	84	75	152
July	22	76	40	69	45	66	71	70	111	61
Aug.	77	44	89	47	41	19	100	56	29	89
Sept.	66	51	19	72	23	57	35	88	158	194
Apr.–Sept.	369	306	285	446	393	433	379	417	531	593
Total year	511	408	475	526	568	575	591	463	648	795
					Growing degree days (base 10°C)					
Apr.–Sept.	1389	1310	1445	1376	1351	1427	1460	1314	1256	1472

† Long-term average precipitation for 1961–1990, Apr–Sept., was 459 mm and yearly average was 581 mm.

yield for each cutting was measured by cutting two 2.43-m^2 samples from each plot. Samples were dried at 60°C and weighed.

Crop residue/grain ratios for corn, soybean, and wheat were measured during crop years 1997 to 2000. Average annual (1997–2000) ratios for each rotation and N treatment were used to calculate crop residue return (based on grain yield) for all years from 1996 through 2005. Plant samples were hand harvested just before field grain harvest. Soybean biomass samples were taken just before leaf drop. The plant material for corn and soybean were cut from four rows 1 m long. The plant material for wheat biomass was cut from four 0.57-m^2 areas. Plants were dried at 60°C and weighed. The total aboveground biomass was separated into grain and crop residue. Grain and crop residues were ground to pass a 0.5-mm sieve and analyzed for C and N content by dry combustion (LECO CN 2000, LECO Corp., St Joseph, MI).

Soil Carbon

In June 1996, 2000, and 2006, six soil cores were taken from 0- to 7.6- and 7.6- to 15.2-cm depths of each plot for analysis of soil C, N, and pH. Soil bulk density was measured for the 2000 and 2006 samplings. Core diameter was 3.2 cm. Samples were dried at 60°C, pulverized, and sieved through a 2-mm sieve. Samples for C and N analysis were further ground and passed through a 0.5-mm sieve. Visible plant material was picked from the soil prior grinding. Soil samples were analyzed for C and N on a LECO 2000 C-N analyzer. Total soil C was considered to be total SOC because the average (81 plots) soil pH of samples collected in 1996 (top 15 cm) was 6.41 (standard deviation = 0.38). Volumetric soil C was calculated using an average of the 2000 and 2006 soil bulk density measurements.

Additional sampling of CC under high N and CSWA under no N was done during 1999 through 2002. Cores were collected for analysis of C, N, pH, and bulk density for 0- to 7.6-, 7.6- to 15.2-, and 15.2- to 30-cm depths. Samples from CSWA were collected from the same plots each year, thus samples were taken during each crop phase of the rotation representing corn, soybean, wheat, and alfalfa. For this special sampling, we collected 20 cores per plot before corn planting, at corn tasseling, and immediately after harvest. These samples were processed and analyzed as described above.

Data Analysis

Comparisons of all measurements were made using one-way and two-way analyses of variance (Minitab Release 14, Minitab, Inc., State College, PA). All treatment factors (N and rotation) in the experiment were considered fixed effects. Years and blocks (replication) were treated as random effects. Treatment means (one-way ANOVA) were separated using Fisher's LSD for all pairwise differences between means. Effects were considered significant for $P \leq 0.05$. The effect of rotation and N (two-way ANOVA) and the interaction of block × rotation and rotation × fertilizer were evaluated using a general linear model. Regression equations were obtained using the Fitted Line Plot feature in Minitab.

Table 2. Average (1997–2000) crop residue/grain ratio and residue C for rotations of continuous corn (CC), corn–soybean (CS), and a 4-yr rotation of corn–soybean–wheat/alfalfa–alfalfa (CSWA). Coefficient of variability (%) shown in parentheses following the mean. Nitrogen fertilizer treatments for corn were corn fertilized for a yield of 8.5 Mg ha^{-1} (high N), corn fertilized for a yield of 5.3 Mg ha^{-1} (mid N), and corn not fertilized (no N).

Rotation	N treatment	Residue/grain ratio			Residue total C		
		Corn	Soybean	Wheat	Corn	Soybean	Wheat
						%	
CC	high N	1.03 (17.8)	–	–	43.64 (3.6)	–	–
	mid N	1.11 (15.2)	–	–	43.23 (4.2)	–	–
	no N	1.25 (16.7)	–	–	42.86 (4.6)	–	–
CS	high N	0.93 (12.9)	1.24 (31.4)	–	43.69 (3.4)	44.75 (2.1)	–
	mid N	0.95 (13.4)	1.23 (27.3)	–	43.79 (3.2)	44.82 (1.8)	–
	no N	0.99 (10.1)	1.28 (23.8)	–	43.38 (4.4)	44.88 (1.9)	–
CSWA	high N	1.06 (13.2)	1.36 (23.2)	1.39 (21.2)	43.53 (3.2)	44.59 (2.2)	44.89 (1.1)
	mid N	0.98 (8.9)	1.41 (19.6)	1.41 (23.8)	43.52 (3.1)	44.85 (1.5)	44.64 (1.4)
	no N	0.99 (9.7)	1.27 (27.2)	1.26 (23.0)	43.59 (3.0)	44.31 (2.0)	44.49 (1.6)

RESULTS AND DISCUSSION

Crop Carbon Return to Soil

Carbon input to the soil from 1996 through 2005 from the aboveground plant biomass was estimated from harvested grain biomass and residue/grain ratios. Details of plot management and corn grain yields for this field experiment have been reported by Pikul et al. (2005). Ratios and C content of residues for all rotations and N treatments are shown in Table 2. Average residue/grain ratios for rotations were 1.03, 1.30, and 1.35 for corn, soybean, and spring wheat, respectively. For comparison, Johnson et al. (2006) estimated source C from crop residues, roots, and rhizodeposits using the national grain-yield database and harvest index and found residue/grain ratios of 0.88, 1.17, and 1.22 for corn, soybean, and wheat, respectively. In a 29-yr study located near Morris, MN, Wilts et al. (2004) reported stover/grain ratios of 1.63, 1.64, and 2.1 for corn fertilized at high, low, and no fertilizer, respectively.

Aboveground plant C and N returned to the soil from 1996 to 2005 for rotations and N treatments are shown in Table 3. Continuous corn annually returned about 34% more aboveground PC (average of N treatments) to the soil than CSWA and 23% more aboveground PC than CS. On average (all N treatments), CSWA returned the least aboveground PC to the soil compared with CC and CS, but residues from CSWA returned the greatest amount of N to the soil (Table 3).

Table 3. Average annual aboveground plant C and N returned to the soil (1996–2005) and change in soil organic C (SOC) of the top 15 cm (1996–2006) for rotations of continuous corn (CC), corn–soybean (CS), and corn–soybean–wheat/alfalfa–alfalfa (CSWA). Nitrogen fertilizer treatments for corn were corn fertilized for a yield of 8.5 Mg ha^{-1} (high N), corn fertilized for a yield of 5.3 Mg ha^{-1} (mid N), and corn not fertilized (no N).

Rotation	Fertilizer N			Avg.
	high N	mid N	no N	
		Plant C, Mg C ha^{-1} yr^{-1}		
CC	2.53	2.27	1.70	2.17 A†
CS	1.87	1.84	1.61	1.77 B
CSWA	1.70	1.64	1.53	1.62 C
Avg.	2.04 a	1.91 b	1.61 c	
ANOVA				
Rotation (R)		***		
Fertilizer (F)		***		
R × F		***		
		Plant N, kg N ha^{-1} yr^{-1}		
CC	34.24	24.71	14.44	24.46 A
CS	53.91	50.84	46.06	50.27 B
CSWA	58.40	56.57	50.17	55.05 C
Avg.	48.85 a	44.04 b	36.89 c	
ANOVA				
Rotation (R)		***		
Fertilizer (F)		***		
R × F		**		
		SOC change, Mg C ha^{-1}		
CC	−2.30	−1.77	−5.86	−3.307 A
CS	−2.54	−2.92	−3.94	−3.135 A
CSWA	0.26	0.30	−0.27	0.094 B
Avg.	−1.52 a	−1.46 a	−3.36 b	
ANOVA				
Rotation (R)		***		
Fertilizer (F)		**		
R × F		NS		

** Significant at the 0.01 level. NS, not significant at the 0.05 level.

*** Significant at the 0.001 level.

† Means followed by different lowercase letters (comparison of N treatments) are significantly different at $P \leq 0.05$. Means followed by different uppercase letters (comparison of rotations) are significantly different at $P \leq 0.05$.

Soil Carbon and Crop Residues

Plots under CC and high N lost 2.3 Mg C ha^{-1} SOC from the top 15 cm of soil from 1996 to 2006 even though 25.3 Mg C ha^{-1} was returned as crop residue during this time (Table 3). There was a significant effect of rotation and fertilizer N addition on SOC sequestration. Under CC and CS, the addition of fertilizer N tended to reduce SOC loss. Under CSWA, fertilizer addition had little effect on SOC change (Table 3). Plots under grass gained about 3.75 Mg C ha^{-1} in the top 15 cm (Fig. 1).

Plant C return to plots under CSWA at all N levels was the least of all rotations (Table 3), but these plots lost the least SOC under no N (–0.27 Mg C ha^{-1}) and made slight gains (average of 0.28 Mg C ha^{-1}) under high and mid N (Fig. 1, Table 3). In a 4-yr rotation cycle, there were 35% fewer tillage operations on CSWA than CC (Table 4). We speculate that a combination of reduced tillage operations and increased crop diversity (crops having different root structures and contributions to soil C and N) under CSWA led to an equilibrium in SOC, where the amount of C returned was approximately equal to C lost. Hooker et al. (2005) suggested, based on findings from long-term residue removal experiments at Peters' Field, University of Connecticut, that new C_4–C (C associated with corn residue) from aboveground biomass might be rapidly cycled back to the atmosphere as CO_2 or lost as dissolved organic C. Furthermore, Hooker et al. (2005) suggested that the annual return of aboveground biomass may not increase SOC storage over the long term on soils near steady-state SOC levels.

There were no significant differences in soil bulk density of the top 15 cm between years or among treatments. Average soil bulk density by rotation was 1.421, 1.432, and 1.419 g cm^{-3} under CC, CS, and CSWA, respectively. Average soil bulk density by year was 1.376 g cm^{-3} in 2000 and 1.365 g cm^{-3} in 2006. For the special samplings of CC under high N and CSWA under

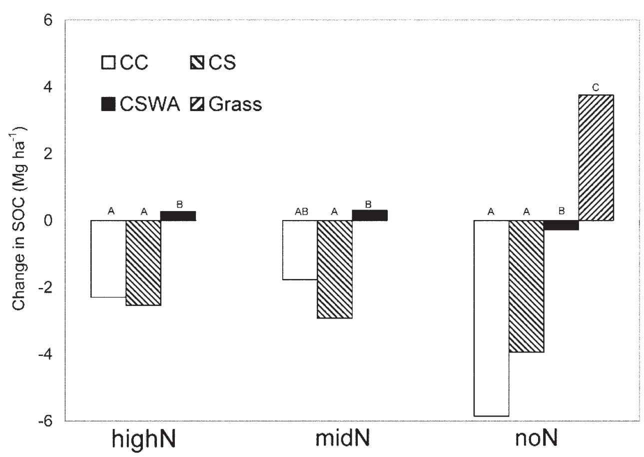

Fig. 1. Change in soil organic C (SOC) in the top 15 cm of soil from 1996 to 2006 under continuous corn (CC), a corn–soybean rotation (CS), a corn–soybean–wheat/alfalfa–alfalfa hay rotation (CSWA), and perennial grass. Means within each N treatment (high N, mid N, and no N) followed by the same letter were not significantly different (0.05 probability level).

Table 4. Typical tillage operations during 4 yr in continuous corn and a 4-yr corn–soybean–spring wheat/alfalfa–alfalfa (CSWA) rotation.

Crop system	Primary tillage moldboard plow† or chisel	Seedbed preparation disk and cultivate	Row cultivation twice per season‡	Total operations
Continuous corn				
Corn	1	2	2	5
Corn	1	2	2	5
Corn	1	2	2	5
Corn	1	2	2	5
Total	4	8	8	20
CSWA rotation				
Corn	1	2	2	5
Soybean	1	2	2	5
Wheat/alfalfa	0	2	0	2
Alfalfa hay	1	0	0	1
Total	3	6	4	13

† Primary tillage conducted in the fall of the year. Moldboard plow was replaced by chisel plow in fall 1996.

‡ Starting in 2000, the number of row cultivations was reduced to one per year.

no N during 1999 through 2002, average soil bulk density of the 15- to 30-cm layer was 1.577 g cm^{-3} under CC with high N and 1.533 g cm^{-3} under CSWA with no N.

Plots within the same rotation and N treatment having the greatest SOC in 1996 also appear to have had the greatest loss of soil C. Figure 2 shows SOC measured at seven times within experimental blocks of CC under high N. Replication 1 had significantly less SOC than Replication 3 in 1996 (Fig. 2). Average (Replications 2 and 3) SOC loss was 0.18 g kg^{-1} yr^{-1}, compared with 0.05 g kg^{-1} yr^{-1} for Replication 1. Concentrations of SOC under CC appear to be in a continuing state of decline, in contrast to CSWA where an equilibrium condition seems to exist (Fig. 3).

For comparison, under mid N, average concentrations of SOC for 1996, 2000, and 2006 were 16.9, 16.1, and 16.1 g kg^{-1} under CC; 18.9, 18.2, and 17.5 g kg^{-1} under CS; and 17.6, 17.4, and 17.8 g kg^{-1} under CSWA. The change in SOC (1996–2006) for CC was −1.77 Mg C ha^{-1}, while it was −2.92 Mg C ha^{-1} under CS and 0.30 Mg C ha^{-1} under CSWA (Table 3).

From 1996 to 2006, the soil C/N ratio decreased more (narrower ratio) under CSWA than CS (Table 5). Under grass, the soil C/N ratio significantly increased (wider ratio) compared with the cropped rotations. The benefit of legumes to soil N supply is well established in the literature (Piper and Pieters, 1922; Peterson and Varvel, 1989; Raimbault and Vyn 1991), and research on our plots has shown positive benefits with respect to N availability and corn grain yield under CSWA (Pikul et al., 2005). Under controlled laboratory conditions, Carpenter-Boggs et al. (2000) found that the soil under CSWA had the potential to mineralize about 56 kg ha^{-1} more N than under CC. There was no significant temporal change in soil pH. Average (rotation and N treatment) pH was 6.41 in 1996 and 6.4 in 2006.

Relationship between Returned Plant Carbon and Soil Organic Carbon

Research in the northern Corn Belt suggests that the balance of C in soil depends on crop yield. Larson et al. (1972) showed that corn, under conventional tillage, provided a net addition to SOC when the annual return of corn stover, on a dry-weight basis, exceeded 6.0 Mg ha^{-1} (approximately 2.6 Mg C ha^{-1}). This equates to a grain yield of about 6.3 Mg ha^{-1}. Johnson et al. (2006) estimated the minimum source C input to maintain SOC from aboveground plant C to be 2.5 ± 1.0 Mg C ha^{-1} yr^{-1} under moldboard-plow systems from 13 field experiments. The mean corn yield (1996–2005) for CC under high N in our study was 6.1 Mg ha^{-1} (Pikul et al., 2005). With a grain yield of 6.1 Mg ha^{-1}, our average yearly C return for CC under high N from aboveground plant material was 2.53 Mg C ha^{-1} (Table 3). Carbon return on our plots roughly fell within the C-balance estimates provided by Larson et al. (1972) and estimated by Johnson et al. (2006), but our CC plots under high N lost SOC in the top 15 cm (Table 3).

Collectively for all rotations and N treatments, there was no apparent relationship between the quantity of aboveground C inputs and the change in SOC in the surface 15 cm (Fig. 4). Average annual C input into these plots ranged from 1.3 to 2.8 Mg C ha^{-1} yr^{-1} across all rotations. When rotations

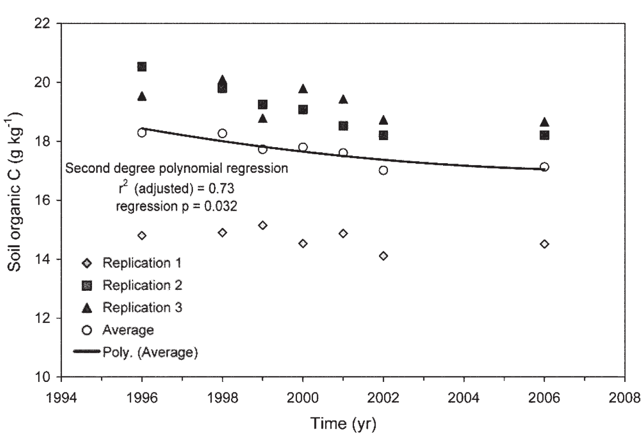

Fig. 2. Soil organic C in the top 15 cm of soil of each replication under continuous corn with high N fertilization from 1996 to 2006.

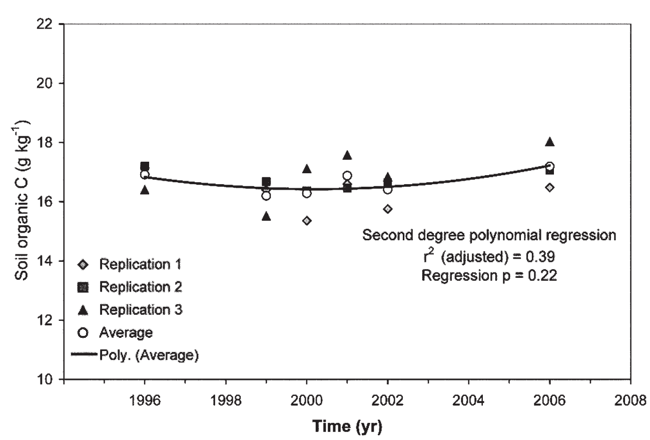

Fig. 3. Soil organic C in the top 15 cm of soil of each replication under a corn–soybean–wheat/alfalfa–alfalfa hay rotation with no N fertilizer from 1996 to 2006.

were examined independently, ΔSOC under CC had a positive linear relationship with C input ($P = 0.1$). The regression equation extrapolated to the point where ΔSOC = 0 suggests that under CC with chisel plow tillage, a minimum aboveground C input of 3.21 Mg ha^{-1} yr^{-1} is required to maintain SOC in the top 15 cm. Johnson et al. (2006) estimated a minimum C return of 2.5 ± 1.0 Mg C ha^{-1} yr^{-1} for continuous corn under moldboard tillage. By comparison, a 29-yr study in western Minnesota, receiving aboveground inputs of 3.3 Mg C ha^{-1} yr^{-1} under moldboard tillage, also lost SOC (Reicosky et al., 2002).

The relationship between the aboveground C input and ΔSOC under CS was poor ($P = 0.17$) when averaging the C contributions from both corn and soybean for each year (Fig. 4). When additions from corn C and soybean C were separated and analyzed independently, however, the relationship between C input and ΔSOC improved ($P = 0.09$) but only for corn-derived C. The regression equation extrapolated to ΔSOC = 0 suggested that 3.61 Mg C ha^{-1} yr^{-1} during the corn phase of the CS rotation was necessary to maintain SOC in the surface 15 cm. The need for additional C inputs during the corn phase supports the assumption of Johnson et al. (2006) and Wilhelm et al. (2007) that more corn C inputs are needed during the corn phase to compensate for the lower biomass returned by soybean.

There are several explanations for the lack of relationship between C input and ΔSOC in the 4-yr rotation (Fig. 4). Possibly the CSWA rotation is near a dynamic equilibrium where plant C return is approximately equal to C loss. In addition or alternatively, the inclusion of perennial alfalfa may contribute more belowground C than the CC or CS rotations, thus compensating for the low aboveground C input (Table 3). Roots contribute more C to SOC than aboveground plant components, as reviewed by Johnson et al. (2006). Alfalfa roots in the top 15 cm of soil have root/shoot ratios ranging from 0.52 to 1.11 during their establishment year (Curran et al., 1993), whereas wheat, corn, and soybean have lower root/shoot ratios of 0.5, 0.32, and 0.37, respectively (Buyanovsky and Wagner, 1997). Others have reported even lower root/shoot ratios for these crops (e.g., Wilhelm et al., 1982; Huggins and Fuchs, 1997; Klepper, 1991). Rhizodeposition of C can also significantly build SOC (Johnson et al., 2006).

CONCLUSION

Under high N fertilizer management for corn, there was a loss of 2.3 Mg C ha^{-1} from the top 15 cm of soil under CC even when all crop residues were returned to the soil. In contrast, and under the same N management plan, there was a gain of 0.3 Mg C ha^{-1} under CSWA. Our findings on C storage are relevant to the top 10 corn production counties in eastern South Dakota as an estimate of reasonable rates of SOC accumulation or loss. With respect to corn production, average (1990–2005) unirrigated corn grain yield was 7.2 Mg ha^{-1} for the top producing counties in South Dakota (NASS, 2005). For comparison, corn yield (1990–2005) for CC under high N in our experiment was 6.8 Mg ha^{-1}.

Corn captures significant amounts of C; however, only a small fraction of plant C may be retained in the soil. For crop years 1996 through 2006, continuous corn under high N returned about 34% more PC to the soil than the CSWA rotation and 23% more aboveground PC than CS. Yet, under high N, the SOC loss with CC was nearly 10-fold greater than with CSWA. On average (all N treatments), CSWA returned the least aboveground PC to the soil compared with CC and CS, but residues from CSWA returned the greatest amount of N. Soil productivity is related to both the quantity of SOC and the quality of soil organic matter as well as other factors. The historic good yield of corn in the CSWA rotation, reported by Pikul et al. (2005), may reflect soil improvement from this rotation.

In this study, despite crop residues being returned to the soil, we showed that the potential to sequester C was very limited under rotated corn (CSWA) and not possible under continuous

Table 5. Soil organic C (SOC) and bulk density in the top 15 cm in 2006 and the change in the soil C/N ratio for the period 1996 to 2006. Crops were continuous corn (CC), corn–soybean (CS), corn–soybean–wheat/alfalfa–alfalfa (CSWA), and grass. Nitrogen fertilizer treatments for corn were corn fertilized for a yield of 8.5 Mg ha^{-1} (high N), corn fertilized for a yield of 5.3 Mg ha^{-1} (mid N), and corn not fertilized (no N).

Crop management	N fertilizer management			Rotation effect
	high N	mid N	no N	
	SOC in 2006, Mg C ha^{-1}			
CC	34.34	33.19	33.81	33.78 A†
CS	35.42	37.24	37.70	36.79 B
CSWA	36.68	37.06	36.97	36.91 B
Grass				44.59 C
P value				***
	Bulk density in 2006, g cm^{-3}			
CC	1.32	1.35	1.32	1.33
CS	1.36	1.40	1.40	1.38
CSWA	1.38	1.37	1.36	1.37
Grass				1.38
P value				NS
	Change in soil C/N ratio, 1996–2006			
CC	−0.36	−0.57	−0.87	−0.60 AB
CS	−0.76	−0.45	−0.53	−0.58 B
CSWA	−0.95	−0.81	−0.95	−0.90 A
Grass				0.48 C
P value				***

*** Significant at the 0.001 level. NS, not significant at the 0.05 level.

† Means followed by different uppercase letters (comparison of rotations) are significantly different at $P \leq 0.05$.

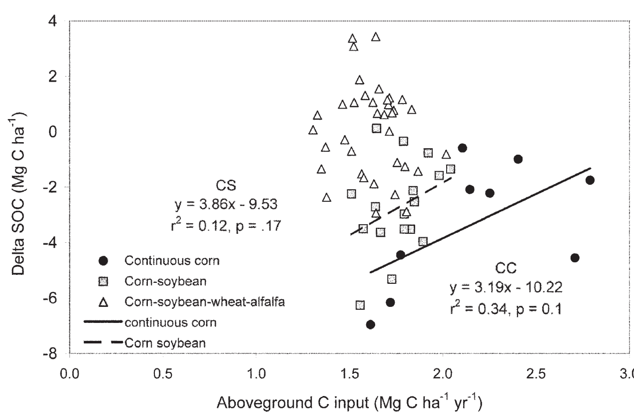

Fig. 4. Change in soil organic C (delta SOC) of the 0- to 15-cm depth of all rotations and N treatments from 1996 to 2006 as a function of average aboveground C inputs from crops grown in 1996 to 2005.

corn grain (CC) at our production levels. A combination of greater crop diversity and fewer tillage operations on CSWA, compared with CC, probably contributed to a balance of SOC where the return of PC approximately equaled the loss of SOC.

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